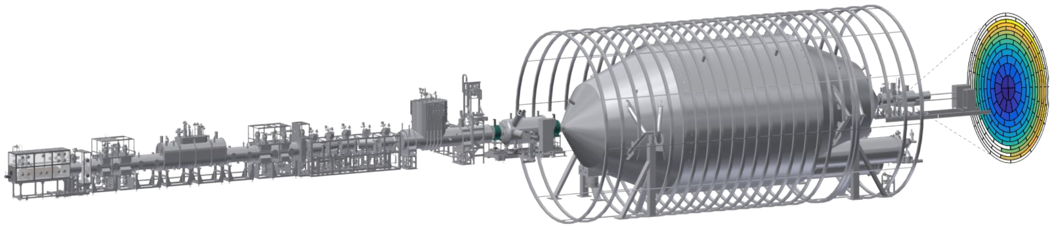
Karlsruhe Institute of Technology



Direct neutrino-mass measurement based on 259 days of KATRIN data

Alexey Lokhov
on behalf of the
KATRIN collaboration

Karlsruhe Institute
of Technology,
Germany

NEUTRINO 2024

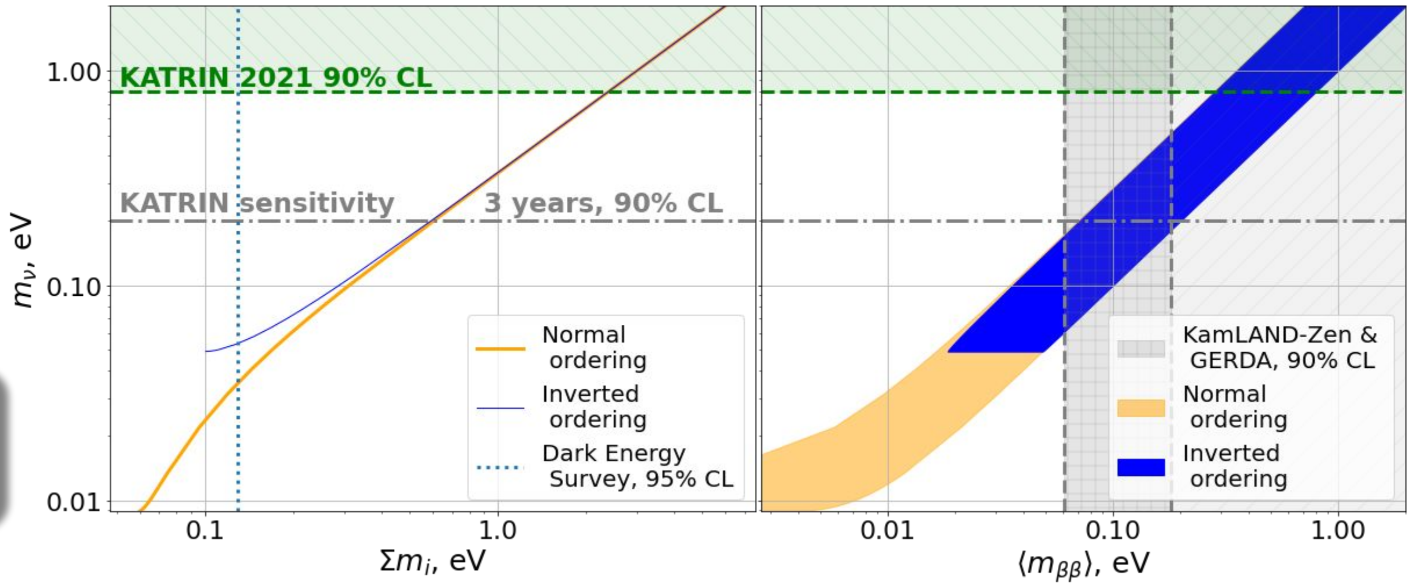
XXXI International Conference on Neutrino Physics and Astrophysics

Milano (Italy) - June 16-22, 2024

Neutrino mass observables

Direct neutrino mass determination

See also overview by A. Nucciotti



Cosmological observables **Neutrinoless double β-decay**

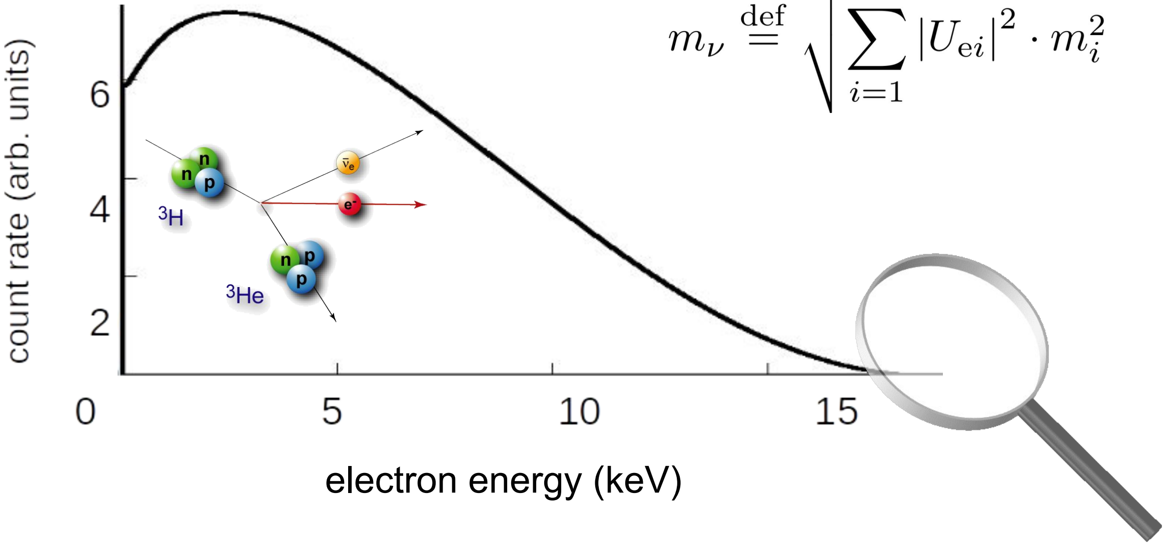
Lokhov, Mertens, Parno, Schlösser, Valerius, Ann.Rev.Nucl.Part.Sci. 72 (2022) 259-282

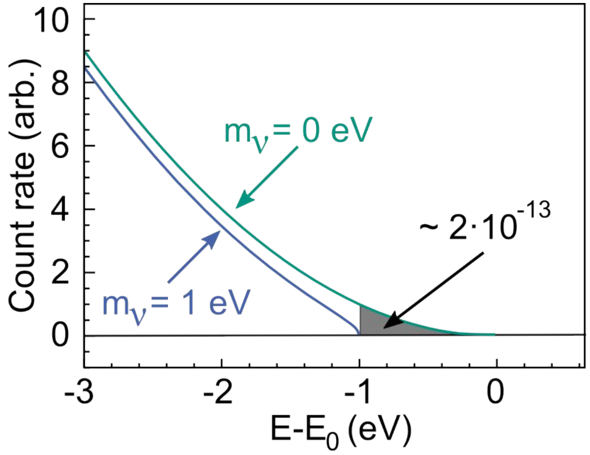
Neutrino mass in tritium β-decay

Measurement of effective mass $\boldsymbol{m_\nu}$ based on **kinematic parameters & energy conservation**

$$R_\beta(E) \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

$$m_\nu \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$





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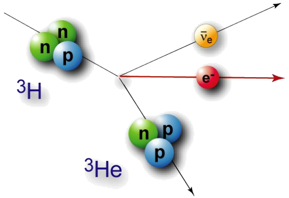
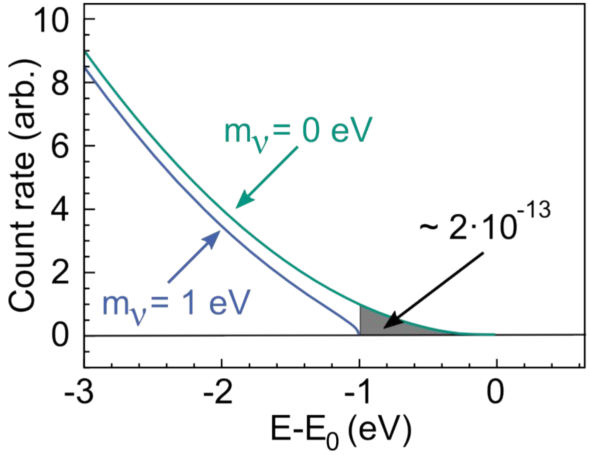
Experimental challenges:

- High source **activity**
- Excellent energy **resolution** (~1 eV)
- Low **background** (≪1 cps)
- Spectrum and response **model**

⇒ Tritium: $\boldsymbol{E_0}$ **= 18.6 keV**, $\boldsymbol{T_{1/2}}$ **= 12 yr**





KATRIN:

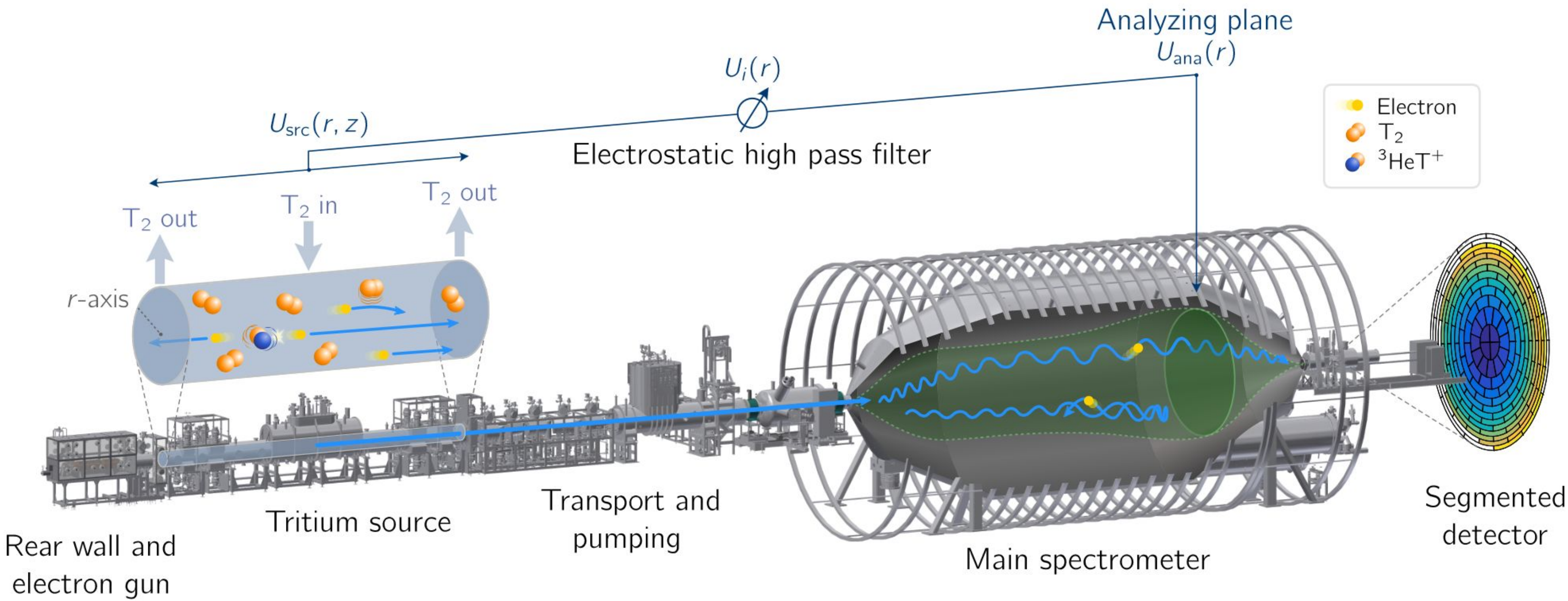
Karlsruhe

Tritium

Neutrino

Experiment

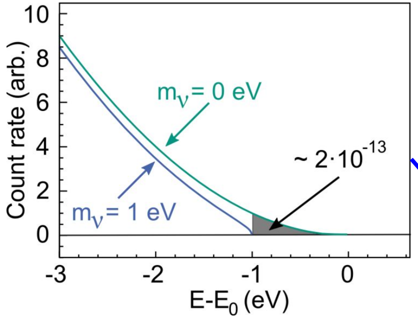
The KATRIN experiment

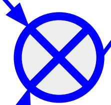


Full system description & commissioning: KATRIN, JINST 16 (2021) T08015

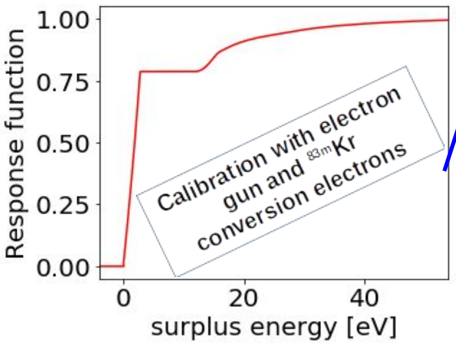
Modelling the tritium spectrum

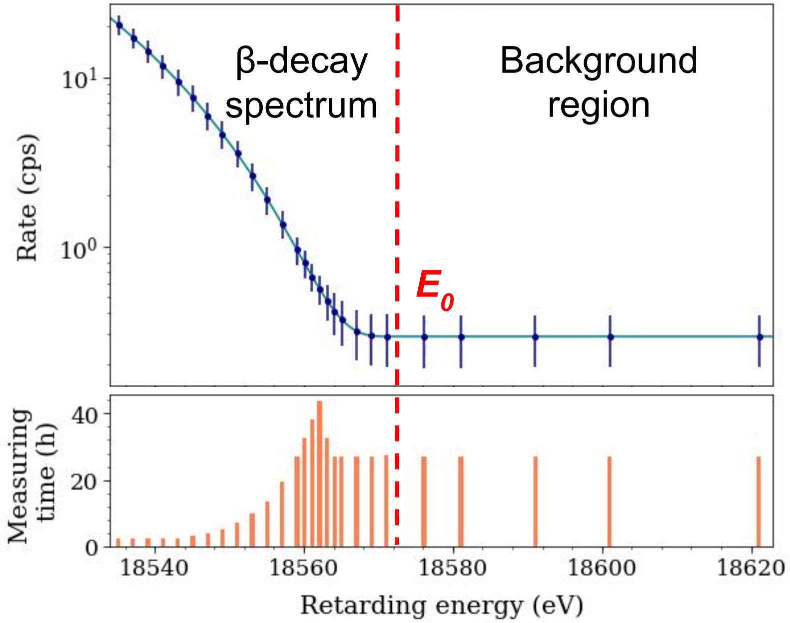
- Beta spectrum: $\boldsymbol{R_\beta(E;m^2(\nu_e),E_0)}$





- Experimental response: $\boldsymbol{f(E-qU)}$

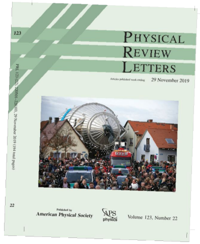


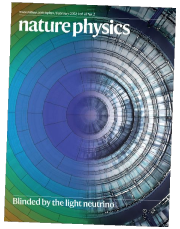


$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E)dE + R_{bg}$$

- **2-3 hour** scans, **O(100)** scans per campaign
- **Stack** data points with the **same** measurement conditions
- Analysis window: **[E_0 - 40 eV, E_0 + 135 eV]**

KATRIN data releases





2019: m_ν < 1.1 eV (90% CL)

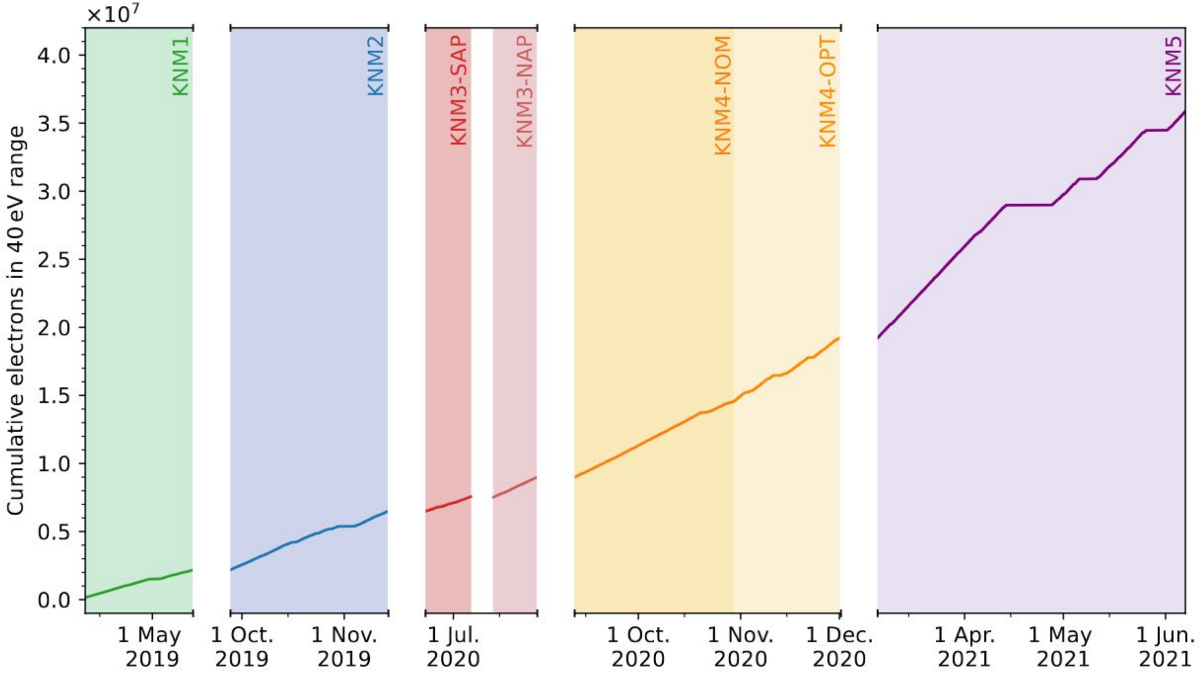
2022: m_ν < 0.8 eV (90% CL)

- **~6** Mio counts

Neutrino 2024:

- **259** measurement days
- **1757** β-scans
- **~36** Mio counts

Expected sensitivity < 0.5 eV



PRL 123 (2019) 221802
PRD 104 (2021) 012005

Nature Phys. 18 (2022) 160

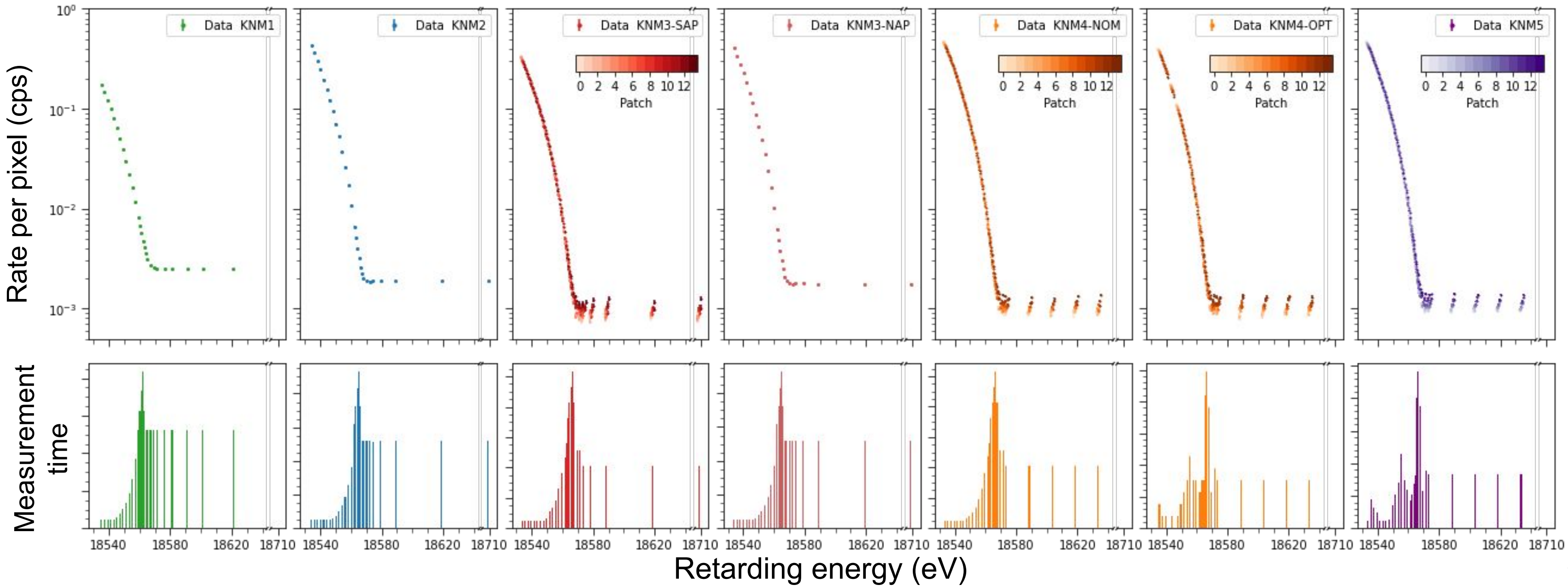
Data

36 Mio counts in total

59 stacked spectra with

27 + 28 + 14 x 28 + 28 + 14 x 28 + 14 x 25 + 14 x 28 =

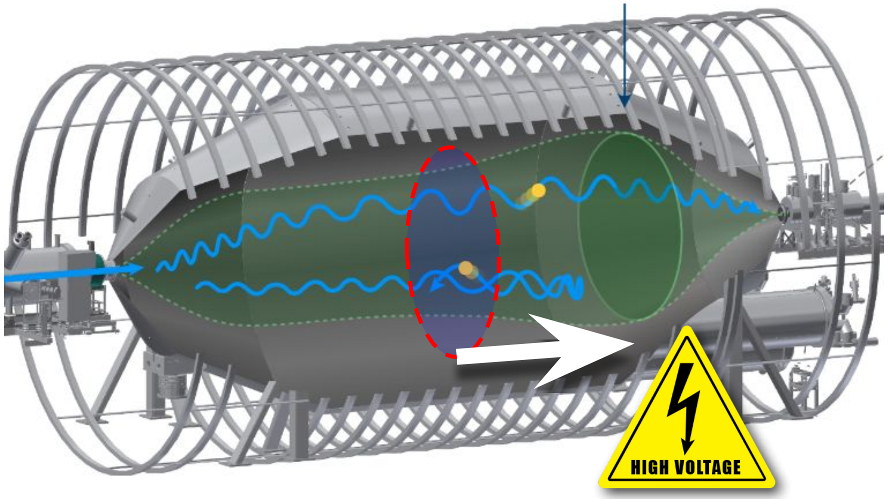
1609 data points

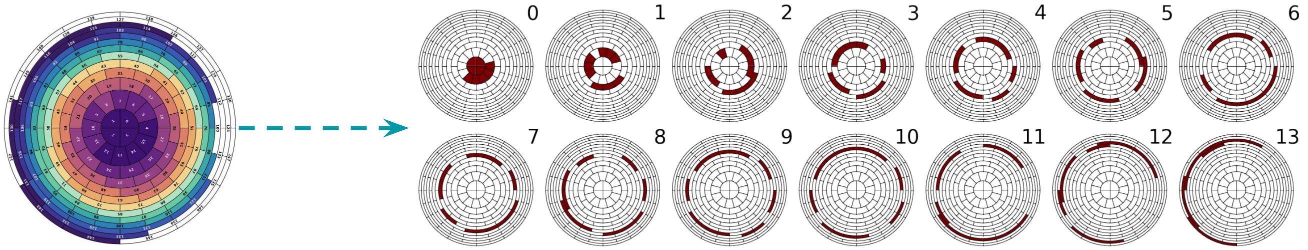


Experimental improvements in new data (I)

Factor 2 lower **background** using “*shifted analyzing plane*” configuration

- Smaller volume mapped onto detector
- Inhomogeneous EM-fields
  - More segmented data **x 14**
  - **Calibration** of fields needed





A. Lokhov et al., Eur. Phys. J. C 82, 258 (2022)

Experimental improvements in new data (II)

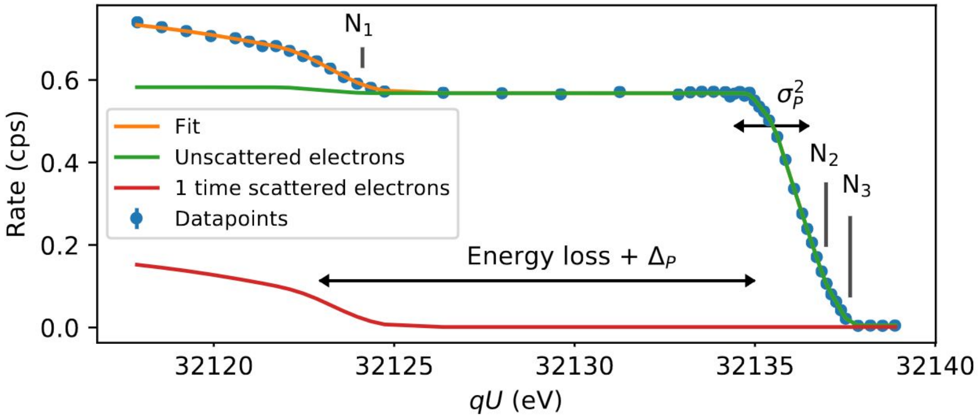
Precise calibration measurements with ^{83m}**Kr** co-circulation:

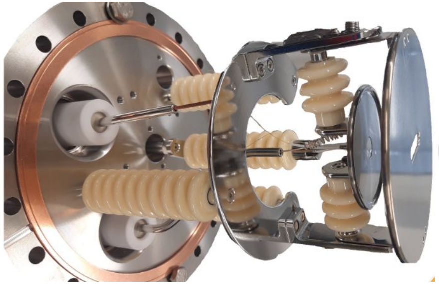
- Probe of electric potential variation in the source
- Field mapping in the spectrometer
- Source temperature: 30K→80K

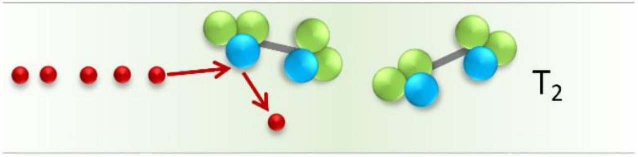
And with the **electron gun**:

- Energy loss through scattering
- Tritium gas density

Spectrum of $N_{1,2,3}$-32 lines of ^{83m}Kr





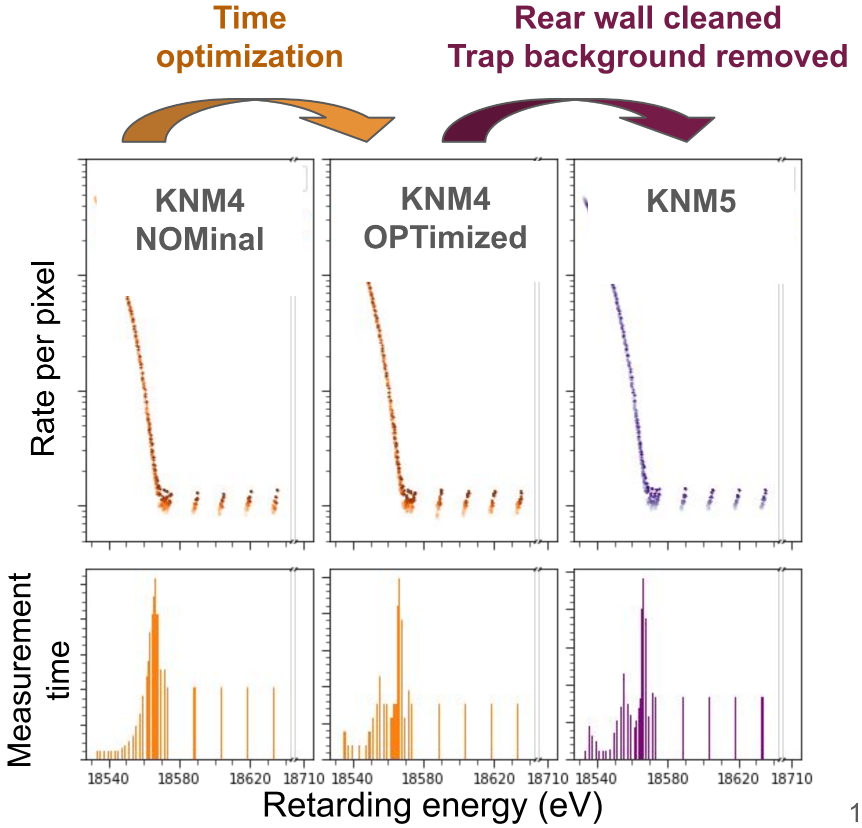


A. Marsteller et al., JINST 17, P12010 (2022); KATRIN collab, Eur. Phys. J. C 81, 579 (2021)

Experimental improvements in new data (III)

In measurement campaigns 4 and 5:

- ➔ **Improved** statistical sensitivity by optimized scan-time distribution
- ➔ **Eliminated** trapped particle background by lowering pre-spectrometer voltage
- ➔ Measured the residual **tritium activity** on the gold-plated **rear wall** and reduced it with ozone cleaning

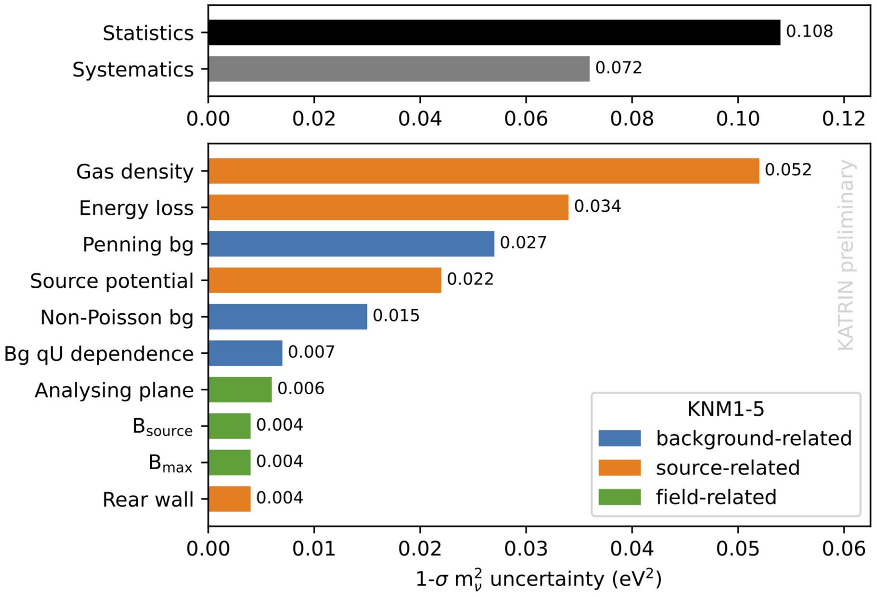


Poster by B. Daniel et al.

M. Aker et al., Fusion Science and Technology 80, 303 (2024)

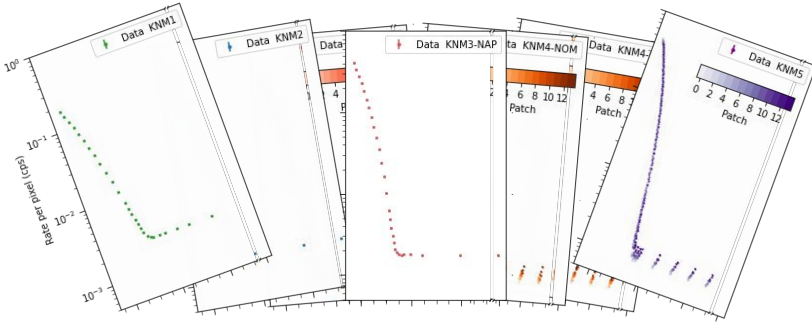
Systematic uncertainties

- **Statistical** uncertainties dominate
- Significant reduction of the **background**-related systematics
- Better control over source **scattering**
  - Increased conservative uncertainties in this release
  - Reduced uncertainties in current data
- **Reduction** of the molecular **final-states** uncertainties
  - Reassessment of theoretical uncertainty estimation: **S. Schneidewind et al., Eur. Phys. J. C 84, 494 (2024)**

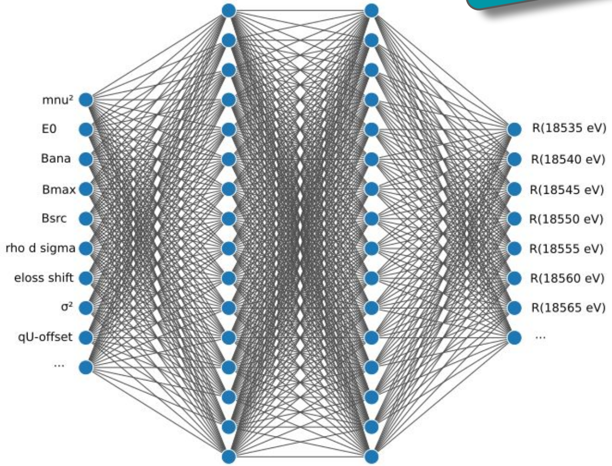


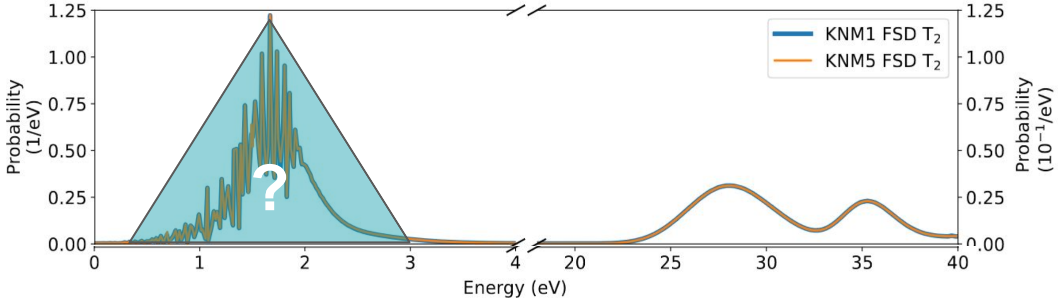
Analysis challenges

- Highly segmented data (**1609** data points)
- Computationally **expensive** model evaluations
- **144** correlated systematic parameters
- **Two** independent analysis teams and frameworks
    - optimized model evaluation
    - fast model prediction with a neural network
- Double-layer **blinding** scheme
    - fixing analysis procedure on MC data
    - using model blinding, unknown modification of final states



Poster by A. Schwemmer

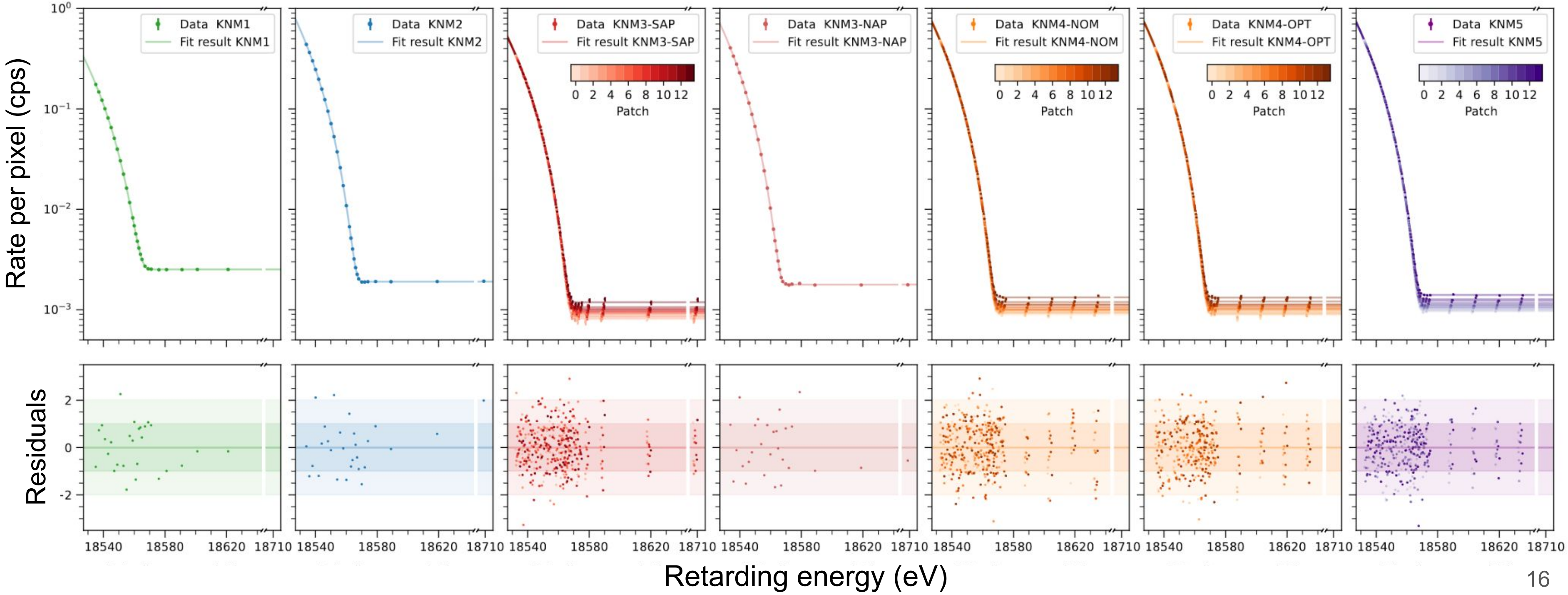




C. Karl, P. Eller, S. Mertens, Eur. Phys. J. C 82, 439 (2022)

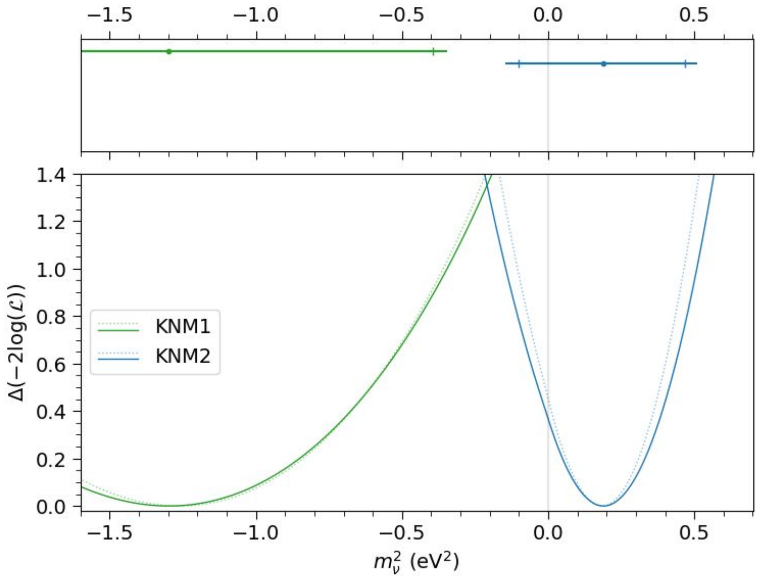
Fit result

- Simultaneous maximum likelihood **fit** with common $\boldsymbol{m_\nu^2}$ parameter
- Excellent goodness-of-fit: **p-value=0.84**



Fit result

- Best-fit value



Fit result

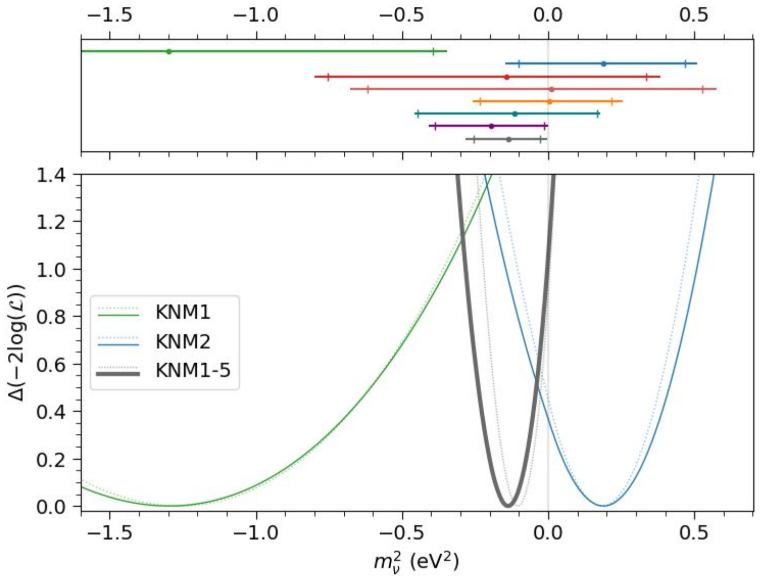
Preprint →
https://www.katrin.kit.edu/130.php#Anker0

- Best-fit value

$$m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$$

- Negative m^2 estimates allowed by the spectrum model to accommodate statistical fluctuations

- Post-unblinding a data-combination mistake was uncovered →
  - Resolved by splitting **KNM4** into **two** data sets
  - ~ 0.1 eV^2 impact on m^2



Q-value: (18 575.0 ± 0.3) eV

Confidence interval

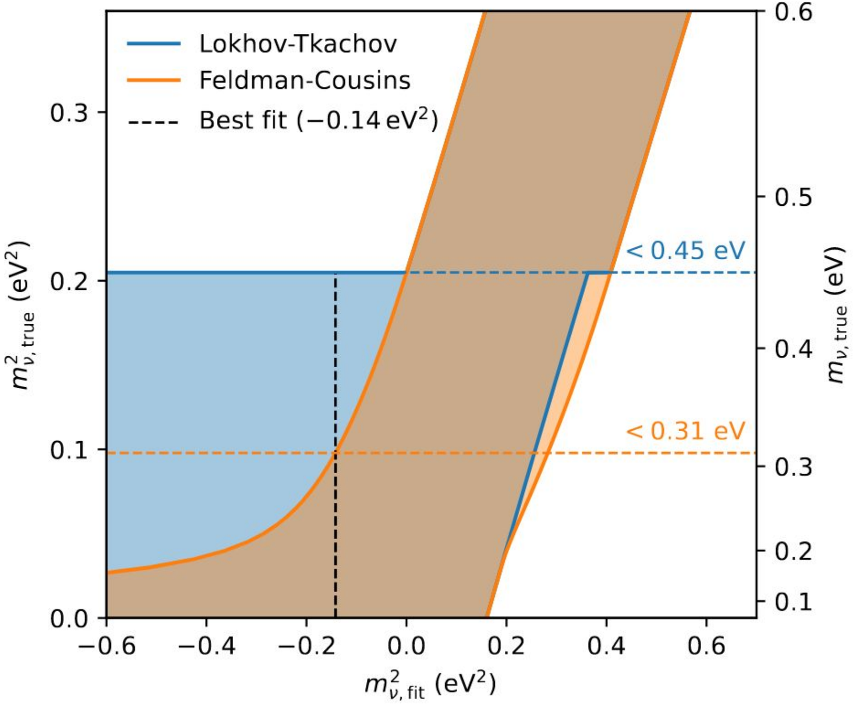
Preprint →
https://www.katrin.kit.edu/130.php#Anker0

- KATRIN's **new** upper limit

$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

  using **Lokhov-Tkachov** construction
- Feldman-Cousins limit:
  - m_ν < 0.31 eV at 90 % CL
  - Shrinking upper limit for negative m_ν^2
- Bayesian analysis in preparation

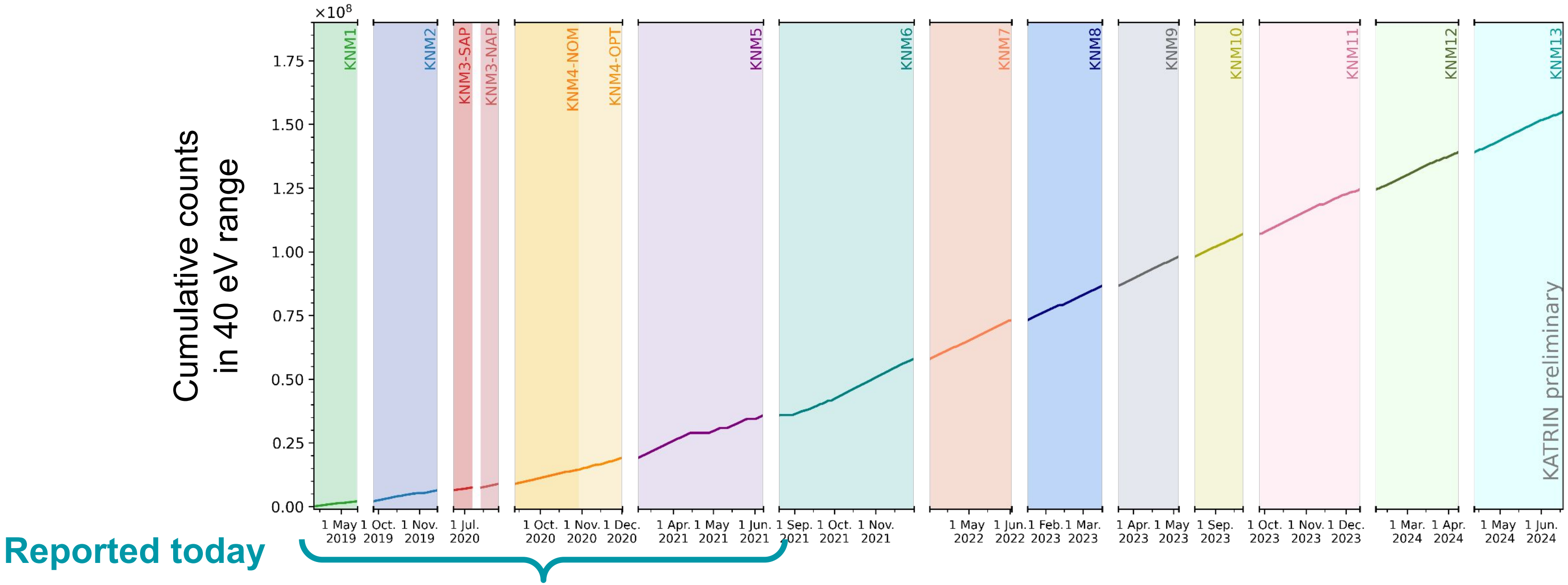
Poster by W. Xu



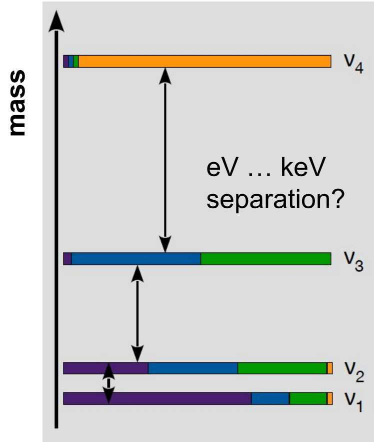
Lokhov, Tkachov, Phys. Part. Nucl. 46 (2015) 3, 347-365
Feldman, Cousins, Phys. Rev. D 57 (1998) 3873-3889

KATRIN data taking continues

- 13 measurement campaigns completed this Monday, June 17!
- **> 150 Mio** counts recorded – **x4** of this release!
- More data to come in **2024-2025** + calibration/systematics improvements



KATRIN "beyond neutrino mass"



Posters by S. Mohanty & X. Stribl

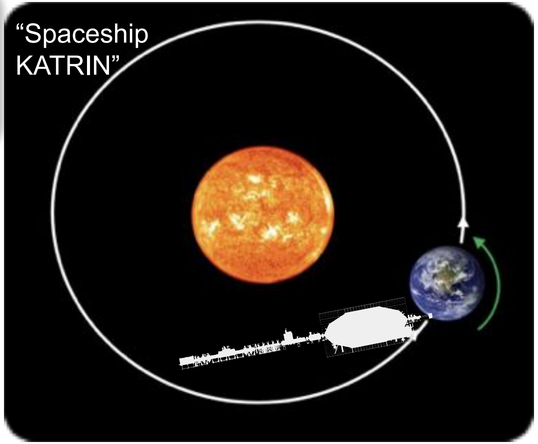
β-spectrum of high statistics and precision

Is there a fourth (sterile) neutrino?
(search for a kink)

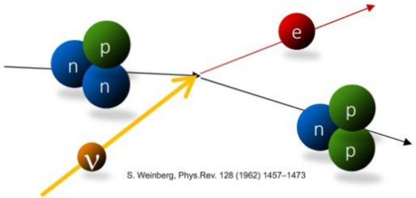
Phys.Rev.Lett. 126 (2021) 9, 091803
Phys.Rev.D 105 (2022) 7, 072004

Search for Lorentz invariance violation
(sidereal modulation)

Phys.Rev.D 107 (2023) 8, 082005



Constrain local density of cosmic relic neutrinos
(peak search)



Phys. Rev. Lett. 129 (2022) 1, 011806

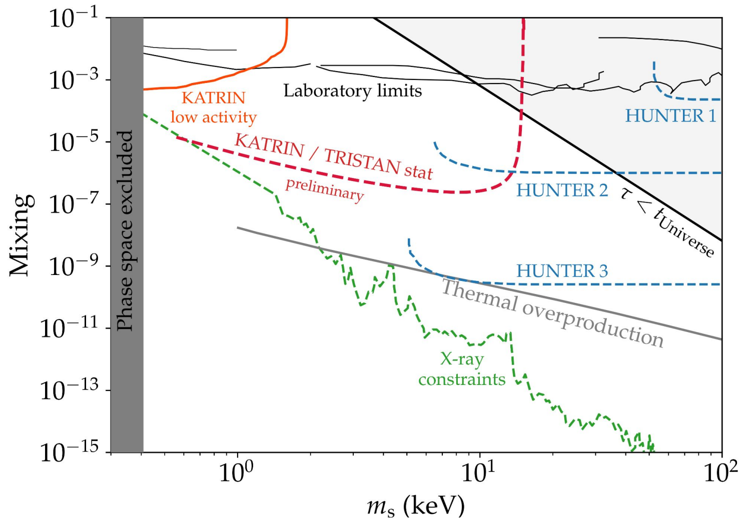
Search for exotic interactions
(spectrum shape)

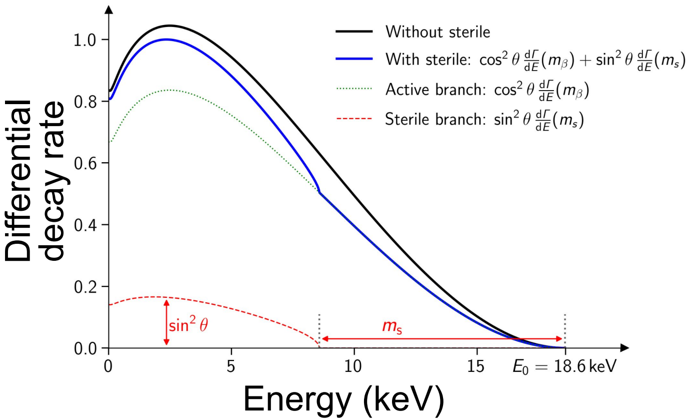
Poster by C. Fengler

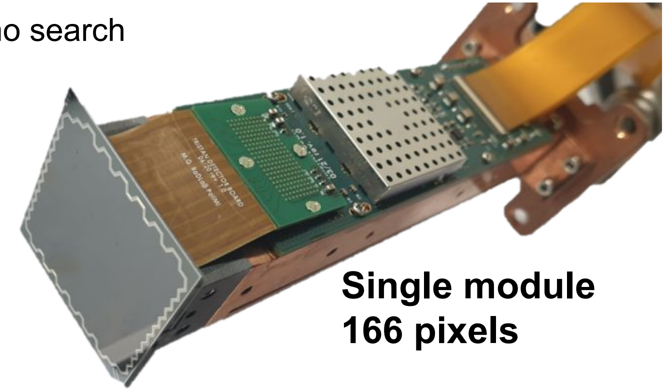
TRISTAN @ KATRIN

Posters by D. Siegmann, A. Onillon & M. Descher

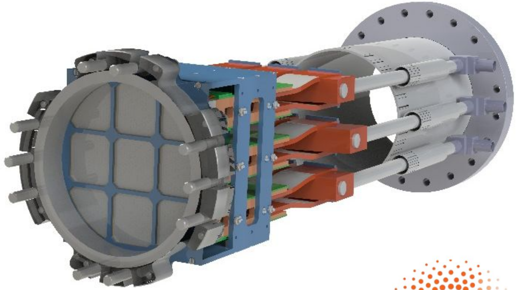
- Search for keV sterile neutrinos
  - Novel SDD array for high rates
- Target sensitivity to mixing of **10^{-6}**
  - Ongoing systematic and modeling studies
- Timeline
  - 2024 – Assembling a full detector replica
  - 2026 – Installation in the KATRIN beamline
  - 2026-2027 – keV sterile neutrino search







Single module
166 pixels



9 modules
~1500 pixels

S. Mertens et al., J. Phys. G46 (2019); S. Mertens et al., J. Phys. G48 (2020); D.Siegmann et al., J. Phys. G (2024)

erc
MAX PLANCK SEMICONDUCTOR LABORATORY
XGLAB BRUKER NANO ANALYTICS

Conclusion and Outlook

Preprint →
https://www.katrin.kit.edu/130.php#Anker0

New KATRIN release improves direct neutrino-mass bound by a factor of 2:

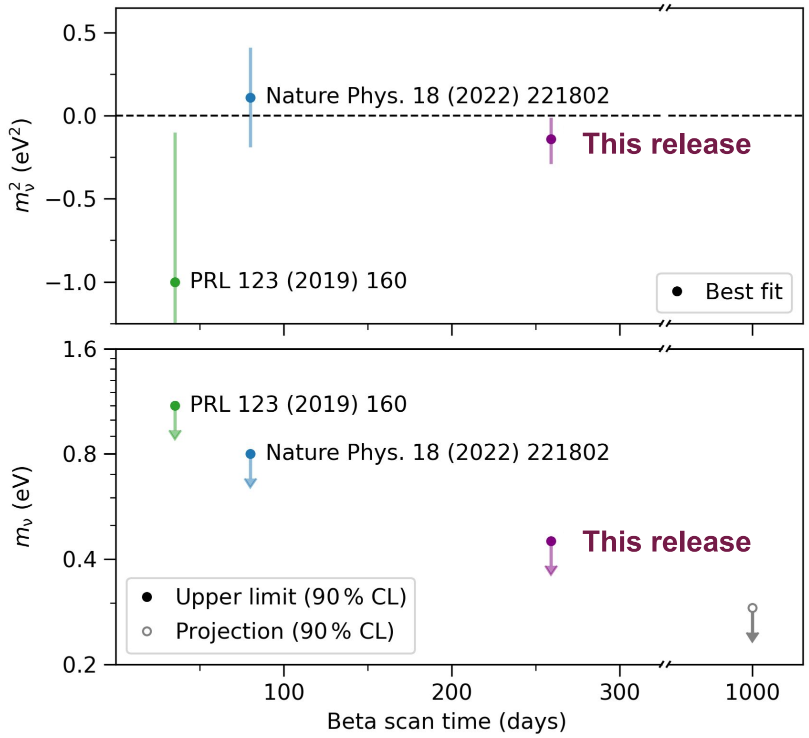
$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

Ongoing analysis:

- 70 % of total anticipated data recorded, improvements in systematics
- Several BSM physics searches: eV-sterile, exotic interactions, light bosons, relic ν… ⇒ stay tuned!

Ongoing data taking through **2025** → **Σ 1000 days**

- target sensitivity below 0.3 eV

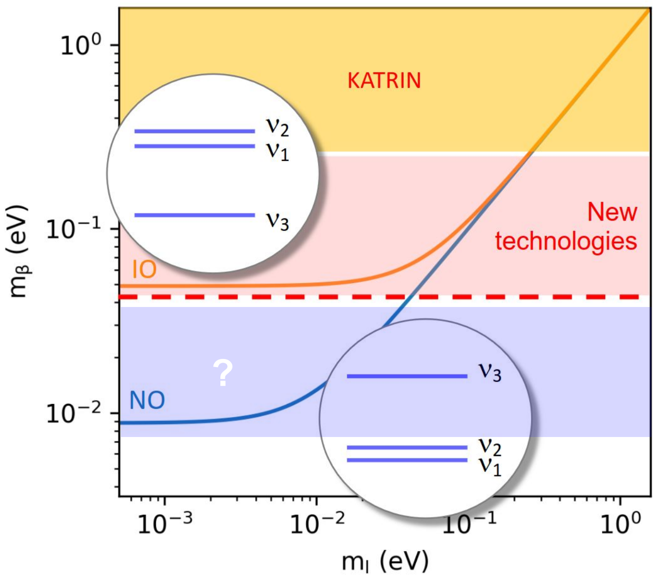


Future perspectives

2026-2027: keV sterile neutrino search with **TRISTAN@KATRIN**

- Preparations for hardware upgrades, analysis is getting ready for the data

2027+: R&D towards the ultimate neutrino mass determination



- Differential methods, atomic tritium, background reduction
- **KATRIN++** mission:
  - Identify and develop scalable technology for the next neutrino mass experiments
  - Use **KATRIN infrastructure** for R&D phase (~7 years)
  - We invite the community to join this effort!

D. Hinz & T. Geigle

A. Nava, M. Biassoni, G. Gagliardi

F. Adam & S. Kempf

C. Rodenbeck & L. Thorne

N. Gutknecht

KATRIN collaboration

Collaboration meeting, March 2024, TUM

KIT Karlsruher Institut für Technologie
MIT
BERKELEY LAB
Humboldt-Universität zu Berlin
Nuclear Physics Institute
cea
TUM
BERGISCHE UNIVERSITÄT WUPPERTAL
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
Max-Planck-Institut für Physik
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
UNIVERSITY of WASHINGTON
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
Carnegie Mellon University
Universität Münster
UAM Universidad Autónoma de Madrid
UNIVERSITÄT BONN
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
INFN
POLITECNICO MILANO 1863
Chula Chulalongkorn University

Bundesministerium für Bildung und Forschung
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
DFG
MAX PLANCK GESELLSCHAFT
U.S. DEPARTMENT OF ENERGY
Office of Science
Czech Republic: MŠMT MINISTRY OF EDUCATION, YOUTH AND SPORTS
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